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Development and application of a methodology for designing a multi-objective and multi-pollutant air quality monitoring network for urban areas

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1. Introduction

Air pollution has been with us since the first fire was lit, although different aspects have been important at different times. Air pollutants are substances which, when present in the atmosphere under certain conditions, may become injurious to human, animal, plant or microbial life, or to property, or which may interfere with the use and enjoyment of life or property. Air pollution is, however enacted on all geographical and temporal scales, ranging from strictly "here and now" problems related to human health and material damage, over regional phenomena like acidification and forest die back with a time horizon of decades, to global phenomena, which over the next centuries can change the conditions for man and nature over the entire globe.

Three classes of factors determine the amount of pollution at a site: a) the nature of relevant emissions, b) the state of the atmosphere and c) topographical aspects.

In this respect the cities act as sources. Cities are by nature concentrations of humans, materials and activities. They therefore exhibit both the highest levels of pollution and the largest targets of impact. Air pollution problems in urban areas generally are of two types. One is the release of primary pollutants and the other is the formation of secondary pollutants. Since a major source of pollutants is motor vehicles, "hot spots" of high concentrations can occur especially near multilane intersections where the emissions are especially high from idling vehicles. The "hot spots" are exacerbated if high buildings surround the intersection, since the volume of air in which the pollution is contained is severely restricted. The combination of these factors results in high concentrations. These cause effects on health and the environment. Increasingly rigorous legislation, combined with powerful societal pressures, is increasing our need for impartial and authoritative information on the quality of the air we all breathe.

Monitoring is a powerful tool for identifying and tackling air quality problems, but its utility is increased when used, in conjunction with predictive modelling and emission assessment, as part of an integrated approach to air quality management (Rao, 2009).

The monitoring of air pollution level is of significance especially to those residents living in urban areas. Planning and location air quality monitoring networks is an important task for environmental protection authorities, involving: a) ensuring that air quality standards are achieved, b) planning and implementing air quality protection and air pollution control strategies, and c) preventing or responding quickly to air quality deterioration. Therefore, environmental protection authorities need to plan and install air quality monitoring networks effectively and systematically. There are no hard and fast rules for air quality network design, since any decisions made will be determined ultimately by the overall monitoring objectives and resource availability.

Before starting the air quality monitoring network design it is essential to establish what problem has to be solved and what constraints have to be imposed on an "ideal" measuring system. The overall objectives of the monitoring network have to be clearly stated. Some of the specific monitoring objectives can be: to quantify ambient air quality and its variation in space and time; to provide data for air pollution control regulations; to provide real-time data for an alert and warning system; to provide trends for identifying future problems or progress against management/control targets; to provide data for development/validation of management tools.

The goals of this study are: a) to develop an objective procedure to determine the monitoring site locations to detect urban background air pollutant concentrations greater than reference concentrations in an urban area, taking into account the consideration of "protection capability" for areas with higher population density, b) to apply the proposed methodology for designing a multi-pollutant (NO_2, CO and PM_{10},) urban air quality network for Buenos Aires city and c) to evaluate "the spatial representativeness" of mean concentrations measured at each monitoring station. The proposed network design methodology is based on the analysis of the results of atmospheric dispersion models; an exceedance score; a population factor and on the application of the t-Student test for comparison air pollutant mean concentrations at different sites.

2. Introduction to Air Quality Monitoring Network Design

Since one cannot expect to monitor air quality at all locations at all times, selection of sites to give a reliable and realistic picture of air quality becomes a problem in the efficient use of limited resources. The selection of monitoring objectives for optimal allocation of air quality monitoring stations may have to cover several design principles. The required design principles usually consist of the considerations of protection capability for regions with higher population density and significant area with higher economic growth as well as the detection capability of higher pollution concentrations, higher frequency of violation of stipulated standards, and the major industrial/traffic sources in an urban region. Moreover, the cost for siting a pollutant-specific monitoring network would be higher than that for a common monitoring network with respect to several pollutants simultaneously. Thus, for practical reasons, most monitoring networks install different detection instruments together in a common monitoring network that could be viewed as more economic and feasible applications.

Even with a clear set of network objectives, there is no universally accepted methodology for implementing such objectives into the network design, with the approaches used being as varied as the regions being managed. Different methodologies on air quality monitoring network design have been reported in the literature. Among them, statistical methods take advantage of the fact that most air quality measurements are correlated either in time at the same location or in space with other monitors in a network. In this way, networks can be optimized by examining time series correlations from long measurement records or spatial correlations among measurements from many nearby monitors (Munn, 1975, 1981; Elsom, 1978). Various statistical and optimization schemes were applied for designing a representative air quality monitoring network with respect to a pollutant-specific case (Smith & Egan, 1979; Graves et al., 1981; Pickett & Whiting, 1981; Egmond & Onderdelinden, 1981; Handscombre & Elsom, 1982; Husain & Khan, 1983; Nakamori & Sawaragi, 1984; Modak & Lohani, 1985a,b; Liu et al, 1986; Langstaff et al., 1987, Hwang & Chan, 1997). Furthermore, Noll & Mitsutome (1983) developed a method to establish monitor locations based on expected ambient pollutant dosage. This method ranked potential locations by calculating the ratio of a station's expected dosage over the study area's total dosage.

It usually happens that an initial monitoring network evolves over time. Therefore after some time a redesign may be required to maximize its capacity to meet modern demands. In this case, it may be desirable the new network maximizes the amount of information it will provide about the environmental field it is being asked to monitor. Equivalently, it should maximally reduce uncertainty about that field. These ideas can be formalized through the use of entropy that quantifies uncertainty and can be used as an objective function. Caselton et al. (1992) used it to rank monitoring sites for possible elimination, an idea extended by Wu & Zidek (1992). Recently, Ainslie et al. (2009) used the entropy-based approach of Le & Zidek (2006) to redesign a monitoring network in Vancouver (Canada) using hourly ozone concentration.

The consideration of multi-pollutant air quality monitoring network design with respect to different objectives was introduced in a series of papers by Modak & Lohani (1985a,b,c). The design principles of a minimum spanning tree algorithm for single or multiple pollutants with respect to one or two objectives was illustrated in these studies. Kainuma et al. (1990) developed a similar procedure to evaluate several types of siting objectives and used a multi-attribute utility function method to determine optimal locations.

Several methods of air quality monitoring design or optimization also include the analysis of atmospheric dispersion models estimations (Hougland & Stephens, 1976; Koda & Seinfeld, 1978; McElroy et al., 1986; Mazzeo & Venegas, 2000, 2008; Tseng and Chang, 2001; Baldauf et al., 2002; Venegas & Mazzeo; 2003a, 2010). For example, Hougland & Stephens (1976) selected monitoring site locations maximizing coverage factors, such as strength of emission source, distance from the source, and local meteorology for each source included in the study. The basis of this "source oriented" method was to consider for each source and wind direction, the monitor with the largest coverage factor. Koda & Seinfeld (1978) presented a methodology for distributing a number of monitoring stations in a study area in order to obtain the maximum sensitivity of the collected data to achieve the variations in the emissions of the sources of interest. The developed methodology used model estimations of ground level concentrations of pollutants for different meteorological scenarios. McElroy et al. (1986) applied air quality simulation models and population exposure information to produce representative combined patterns and then employed the concept of 'sphere of influence' (SOI) developed by Liu et al. (1986) to determine the minimum number of sites required. The monitor's SOI is defined as the area over which the air quality data for a given station can be considered representative, or can be extrapolated, with known confidence. The site's SOI can be determined using the covariance structure of the concentrations. Thus, a monitor site's SOI comprises those neighbouring sites whose variance can be explained by the original site's variance within a certain degree of confidence.

Tseng & Chang (2001) integrated a series of simulation and optimization techniques for generating better siting alternatives of air quality monitoring stations in an urban environment. The analysis presented used atmospheric dispersion models to estimate air pollution concentrations required in the optimization analysis. Three planning objectives for the minimization of the impacts of the highest concentrations and the highest frequency of violation, as well as the maximization of the highest protection potential of population were emphasized subject to budget, coverage effectiveness (the ratio between effective detection area and total detection area for a monitoring station), spatial correlation, or concentration differentiation constraints. In this case, the concentration differentiation constraints takes into account that the spatial correlation between grids can be high, but the order of magnitude of measured or predicted concentrations between both grids may present significant difference, given the fact that grids are only spatially correlated in terms of concentration pattern.

Baldauf et al. (2002) presented a simple methodology for the selection of a neighbourhood-scale site for meeting either of the following two objectives: to locate monitors at the point of maximum concentration or at a location where a population oriented concentration can be measured. The proposed methodology is based on analyzing middle-scale (from 100 to 500 m) atmospheric dispersion models estimations within the area of interest.

Sarigiannis & Saisana (2008) presented a method for multi-objective optimization of air quality monitoring systems, using both ground-based and satellite remote sensing of the troposphere. This technique used atmospheric turbidity as surrogate for air pollution loading. In their study, Sarigiannis & Saisana (2008) also defined an information function approach combining the values of the violation score, the land-use score, the population density, the density of cultural heritage sites and the cost function. Furthermore, similarities among locations were assessed via the linear correlation coefficient between locations. A gain of information was defined as the product between the correlation coefficient and the information function. The location with the maximum value of the gain information was selected as the best monitoring location.

Elkamel et al. (2008) presented an interactive optimization methodology for allocating the number of sites and the configuration of an air quality monitoring network in a vast area to identify the impact of multiple pollutants. They introduced a mathematical model based on the multiple cell approach to create monthly spatial distributions for the concentrations of the pollutants emitted from different emission sources. These spatial temporal patterns were subject to a heuristic optimization algorithm to identify the optimal configuration of a monitoring network. The objective of the optimization was to provide maximum information about multi-pollutants emitted from each source within a given area.

Pires et al. (2009) applied principal component analysis to identify redundant measurements in air quality monitoring networks. To validate their results, authors used statistical models to estimate air pollutant concentrations at removed monitoring sites using the concentrations measured at the remaining monitoring sites.

Mofarrah & Husain (2010) presented an objective methodology for determining the optimum number of ambient air quality stations in a monitoring network. They developed an objective methodology considering the multiple-criteria, including multiple-pollutants concentration and social factors such as population exposure and the construction cost. The analysis employed atmospheric dispersion model simulations. A multiple-criteria approach in conjunction with the spatial correlation technique was used to develop an optimal air quality monitoring network design. These authors used triangular fuzzy numbers to capture the uncertain (i.e., assigning weights) components in the decision making process. The spatial area coverage of the monitoring station was also determined on the basis of the concept of a sphere of influence.

3. Proposed Methodology

The purpose is to design a multi-pollutant air quality monitoring network for an urban area, considering two objectives: one is the detection of higher pollutant concentrations and the other is the "protection capability" for areas with higher population density. The first one is analysed measuring the potential of a monitoring site to detect violations of reference concentrations in terms of violation scores.

The proposed approach consists of seven steps. The first step is to select the air pollutants of concern and their reference concentration levels for each averaging time less-equal 24h. The values for different intervals of reference concentrations can be chosen based on air quality guideline values for the selected pollutants. Furthermore, weighing factors are defined to penalize the exceedance of higher reference concentrations with regard to exceedance of lower ones.

The second step is to apply atmospheric dispersion models to compute the time series of pollutant concentrations in each grid cell in which the urban area is divided.

In the third step an exceedance score (ES_k) of pollutant k is computed for each grid cell. ES_k is given by the following equation (Modak & Lohani, 1985b):

$$ES_k = \sum_{i=1}^{N_k}\sum_{j=1}^{n_k} \frac{(\omega_{j+1} - \omega_j)(C_{i,k} - CR_{j,k})Z}{(CR_{(j+1),k} - CR_{j,k})} \tag{1}$$

where $C_{i,k}$ is a simulated concentration value of pollutant k, N_k is the number of concentration values ($C_{i,k}$) of pollutant k, ω_j is the weighing factor corresponding to the reference value $CR_{j,k}$, n_k is the number of reference values for each pollutant, Z is a factor defined by

$$Z \begin{cases} 1 & C_{i,k} > CR_{j,k} \\ 0 & C_{i,k} \leq CR_{j,k} \end{cases} \tag{2}$$

The fourth step is to evaluate a population factor (PF) for each grid cell, defined by

$$PF = \frac{P}{P_T} 100 \tag{3}$$

where P is the number of inhabitants in the grid cell, P_T is the total population in the urban area.

In the fifth step the total score (TS) defined by Equation (4) is evaluated for each grid cell.

$$TS = PF \sum_{k=1}^{M} ES_k \tag{4}$$

where M is the number of pollutants (if one pollutant has more than one averaging time, each of them has to be considered separately).
In the sixth step the grid cells are ranked according to TS values. The location with the maximum TS value is selected as the best monitoring location. All grid squares located nearer than a given distance (D) (for example, 1 km) to the selected one, are discarded for further site selections. The next site locations are determined according to the same procedure. The number of locations is arbitrary (usually limited by the economical constraint). All grid cells with high TS separated more than distance a D are selected for installing a monitoring station. These selected grid cells constitute the preliminary network.
The seventh step is to evaluate if average concentrations of each pollutant at near selected sites are significantly different. Considering one pollutant at a time, and using the t-Student test, if the difference between mean concentrations at a pair of near sites is statistically significant at the 99% confidence level, both sites remain in the network. Otherwise, the site with less TS can be eliminated from the preliminary network. This procedure is repeated considering all sites. The proposed network is obtained in this step.
Furthermore, "the spatial representativeness" of the monitoring sites of the proposed network can be evaluated. Applying the t-Student test to each pollutant mean concentration, "the spatial representativeness" of each monitoring site can be given by all the near grid cells where mean concentrations are not statistically significant different at the 99% confidence level.

4. Application to the city of Buenos Aires

4.1 The city of Buenos Aires and its surroundings

The city of Buenos Aires (34°35'S – 58°26'W) is the capital of Argentina and is located on the west coast of the de la Plata River. It has an extension of 203km² and 3058309 inhabitants (INDEC, 2008). The city (Fig. 1) is surrounded by the Greater Buenos Aires (24 districts) of 3627km² and 9575955 inhabitants. Both the city of Buenos Aires and the Greater Buenos Aires form the Metropolitan Area of Buenos Aires (MABA), which is considered the third megacity in Latin America following Mexico City (Mexico) and Sao Paulo (Brazil).

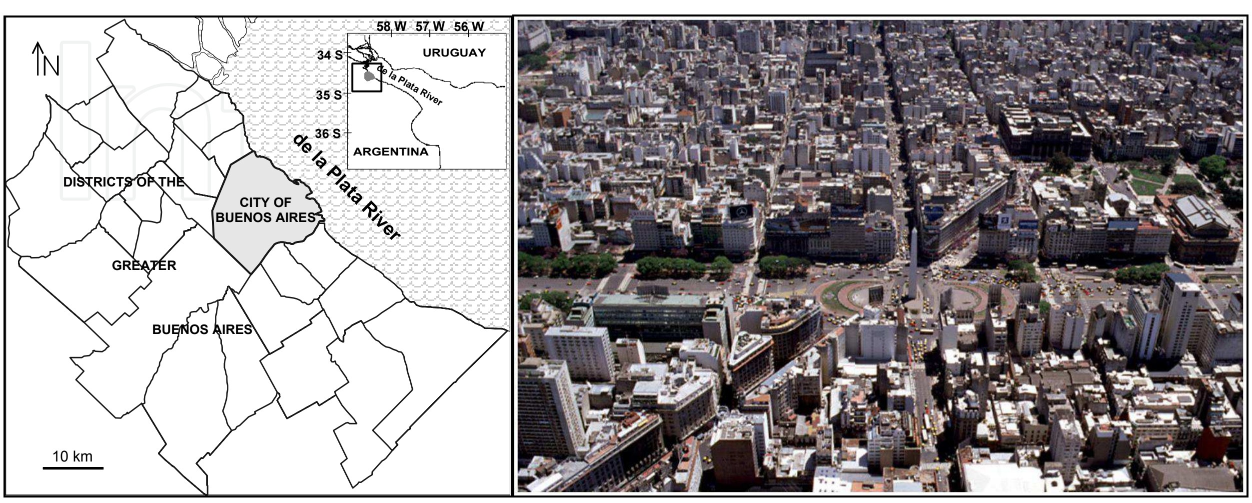

Fig. 1. Location of the city of Buenos Aires and an aerial view of Buenos Aires city.

The MABA is located on a flat terrain with height differences less than 30 m. The de la Plata River is a shallow estuary of 35000km^2, approximately. It is 320km length, and its width varies from 38km to 230km in the upper and lower regions, respectively. In front of the city, the width of the river is about 42km. Mean water temperature varies from 12°C in winter to 24°C in summer. The de la Plata River plain has a temperate climate. The city is hot and humid during summer months (December to February), with a mean high temperature of 27°C. Fluctuating temperatures and quickly changing weather conditions characterise autumn and spring seasons. The winter months (June to August) are mild but humid, with a mean minimum temperature of 6°C. The annual average temperature is 18°C in the city, and it varies between 15-16°C in the suburbs. In the city, frost may occur from June to August, but snowfall is extremely rare. The annual rainfall varies between 900mm and 1600mm, influenced by winds that advect humidity from the Atlantic Ocean. Rainfall is heaviest in March. Winds are generally of low intensity. Strong winds are more frequent between September and March, when storms are more frequent. Annual frequency of winds blowing clean air from the river towards the city is 58%.
The air quality in the city has been the subject of several studies carried out during the last years. Some of these studies analysed data obtained from measurement surveys of pollutants in the urban air (Bogo et al., 1999, 2001, 2003; Venegas & Mazzeo, 2000, 2003b; Mazzeo & Venegas, 2002, 2004; Mazzeo et al., 2005; Bocca et al., 2006). Other studies reported results of the application of atmospheric dispersion models (Venegas & Mazzeo, 2005, 2006). In the Greater Buenos Aires, very few air quality measurements have been made (Fagundez et al., 2001, SAyDS, 2002).

4.2. Emission inventory for the city of Buenos Aires

Mazzeo & Venegas (2003) developed a first version of CO and NO_x (expressed as NO_2) emission inventory for Buenos Aires city. Also Pineda Rojas et al. (2007) presented an emission inventory of these pollutants for the Metropolitan Area of Buenos Aires which includes updated emissions for the city of Buenos Aires. An emission inventory of particulate matter (PM_{10}) for the city of Buenos Aires has been presented by Venegas & Martin (2004). The inventories for the city of Buenos Aires include: a) area sources: residential, commercial, small industries, aircrafts LTO (landing/take-off) cycles at the domestic airport, and road traffic (cars, trucks, taxis, buses) and b) point sources: stacks of three Power Plants. The spatial resolution of the inventories is 1x1 km and a typical hourly variation. The emission factors used in preparing the emission inventories were derived considering: a) monitoring studies undertaken in Buenos Aires (Rideout et al., 2005); b) the EMEP/CORINAIR Atmospheric Inventory Guidebook (EMEP/CORINAIR, 2001); c) the US Environmental Protection Agency's manual on the Compilation of Air Pollution Emission Factors (EPA, 1995). These factors were applied to fuel consumption, gas supply data and vehicle kilometres travelled within each grid square. Data on traffic flow, fleet composition and bus service frequencies was also available. Aircraft emissions were computed knowing the scheduled hourly flights, the type of aircraft, the information available on LTO (landing/take-off) cycles and emission factors (Romano et al, 1999, EMEP/CORINAIR, 2001). Spatial and temporal dependent NO_x (expressed as NO_2), CO and PM_{10} emission distributions in the Buenos Aires Metropolitan Area were obtained.
Figs. 2, 3 and 4 show in diagrammatic form the distribution of annual emission of NO_x (expressed as NO_2), CO and PM_{10} by source category, for the city of Buenos Aires. Since the

Power Plants burn natural gas most of the year and consume fuel oil as much as twenty days in wintertime only, they are responsible for approximately, 51.6% of NO_x (expressed as NO_2), 0.02% of CO and 2.3% of PM_{10} total annual emissions in the city. Carbon monoxide and particulate matter are very much associated with emissions from road traffic. Within Buenos Aires city, road traffic is responsible for 43% of NO_x (expressed as NO_2), 99.43% of CO and 94% of PM_{10} annual emissions in the city.

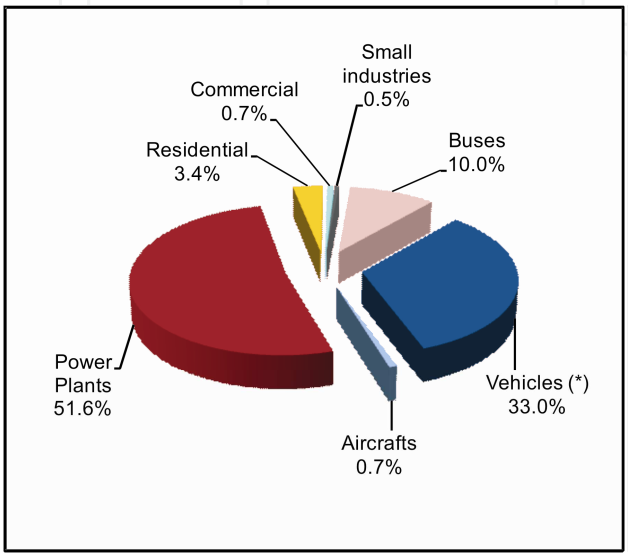

Fig. 2. Estimated emissions of NO_x (expressed as NO_2) by source category. (*) cars, taxis, trucks

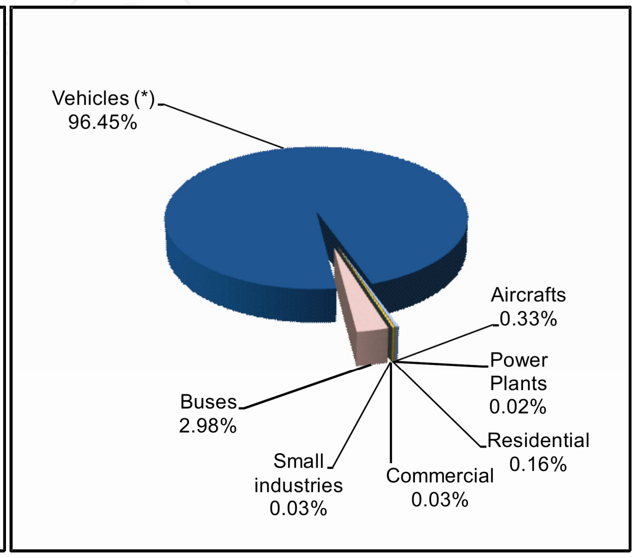

Fig. 3. Estimated emissions of CO by source category. (*) cars, taxis, trucks

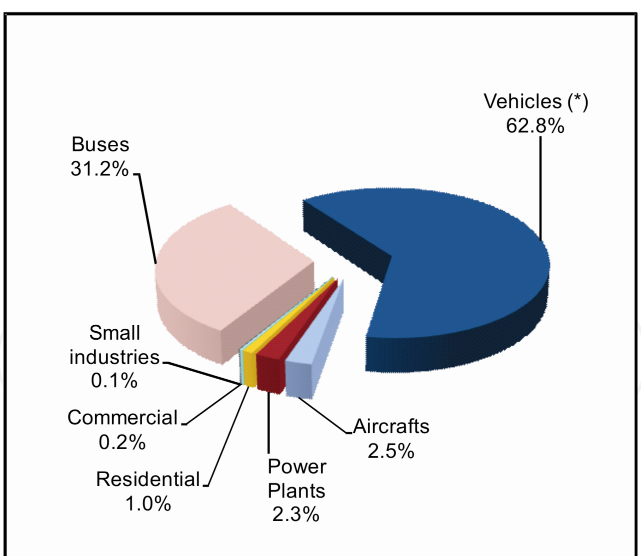

Fig. 4. Estimated emission of PM_{10} by source category. (*) cars, taxis, trucks

4.3. Brief description of the atmospheric dispersion models used in this study

In this work, area sources and point sources contributions to air pollutant concentrations in the city are estimated applying the following atmospheric dispersion models: a) DAUMOD model for urban area sources and b) AERMOD model for urban point sources.

The DAUMOD model

The DAUMOD urban atmospheric dispersion model can be used to estimate background concentrations due to area source emissions. This model has been described elsewhere (Mazzeo & Venegas, 1991; Venegas & Mazzeo, 2002, 2006) however a brief description of it is included. In the development of the DAUMOD model (Mazzeo & Venegas, 1991), a semi-infinite volume of air, bounded by the planes z=0 and x=0 is considered. According with Gifford (1970), for steady-state conditions, with the x-axis in the direction of the mean wind and the z-axis vertical, the concentration [C(x,z)] of pollutants emitted from an area source at the surface, satisfies the bi-dimensional diffusion equation :

$$u(z)\frac{\partial C(x,z)}{\partial x} = \frac{\partial}{\partial z}\left[K(z)\frac{\partial C(x,z)}{\partial z}\right] \quad (5)$$

because only the vertical diffusion contributes significantly to the process. In Equation (5), u(z) is the mean wind speed and K(z) is the vertical eddy diffusivity for contaminants. If the effluents are emitted continuously from the surface level with source strength (Q) expressed as mass per unit area per unit time, the concentration [C(x,z)] satisfies the lower boundary condition:

$$K(z)\left.\frac{C(x,z)}{z}\right|_{z=0} = -Q \quad (6)$$

Another basic assumption is that at a given distance, the vertical extension of the plume of contaminants is h(x), where C(x,h(x)) = 0. Then, there is no transport of mass through the upper limit of the plume, and this can be expressed as:

$$K(z)\left.\frac{C(x,z)}{z}\right|_{z=h} = 0 \quad (7)$$

The boundary condition C(x,h(x))= 0, can be satisfied assuming that the solution of Equation (5) is given by the following polynomial form:

$$C(x,z) = C(x,0)\sum_{j=0}^{6} A_j\left(\frac{z}{h}\right)^j \quad (8)$$

The coefficients A_j have been computed fitting Equation (8) to the results given by the following expression (Pasquill & Smith, 1983):

$$C(x,z) = C(x,0)\exp\left[-4.605\left(\frac{z}{z_m}\right)^s\right] \quad (9)$$

where s is a shape factor which depends on atmospheric stability and surface roughness (Gryning et al., 1987) and z_m is the height at which $C(z_m) = 0.01C(0)$. The height z_m is usually considered to be the upper limit of the plume, so we assumed h= z_m. Considering different atmospheric stability conditions, the coefficients (A_0, A_1,….A_6) of the polynomial of grade 6 are obtained for each fitting.

Atmospheric stability	Expressions for $A_j(z_0/L)$
$z_0/L < -10^{-2}$	$A_j = A_j(z_0/L=-0.01)$
$-10^{-2} \le z_0/L < -10^{-4}$	$A_0 = 1.0$ $A_1 = -9.254667- 0.8043134 \ln(\lvert z_0/L \rvert)$ $A_2 = -26.88303107 - 197.989893 [\ln(1.2146 \lvert z_0/L \rvert)]^{-1}$ $A_3 = -38.00005 + \exp[4.16612 - 373.1065 \lvert z_0/L \rvert)]$ $A_4 = -84.48740174 - 333.915544 [\ln(7.5651 \lvert z_0/L \rvert)]^{-1}$ $A_5 = -33.25054 + \exp[4.13875 - 289.5308 \lvert z_0/L \rvert)]$ $A_6 = -14.47563571 - 43.4735075 [\ln(14.5776 \lvert z_0/L \rvert)]^{-1}$
$-10^{-4} \le z_0/L \le 10^{-4}$	$A_0 = 1.0$ $A_1 = 3853.3 (z_0/L) - 1.461$ $A_2 = -18740 (z_0/L) - 6.797$ $A_3 = 27740 (z_0/L) + 26.931$ $A_4 = -16270 (z_0/L) - 39.652$ $A_5 = 965 (z_0/L) + 27.781$ $A_6 = 1635 (z_0/L) - 7.655$
$10^{-4} < z_0/L$	$A_0 = 1.0$ $A_1 = -0.05478233 - 0.0001021171 [\ln[(z_0/L)+1]]^{-1}$ $A_2 = -6.55023478 + 0.02035983 [\ln(z_0/L)]^3 +0.00191583[\ln(z_0/L)]^4$ $A_3 = 12.9282233 + \exp[2.917612 -1007.8064 (z_0/L)]$ $A_4 = -0.59677391 + 0.05583574 [\ln(z_0/L)]^3 +0.00040899[\ln(z_0/L)]^4$ $A_5 = -1.9551195 + \exp[3.5211141 -1255.2843 (z_0/L)]$ $A_6 = 2.66883478 + 0.00810494[\ln(z_0/L)]^3 -0.00053199[\ln(z_0/L)]^4$

Table 1. Expressions of $A_j(z_0/L)$ as functions of (z_0/L)

The fittings of polynomial form given by Equation (8) to the results of Equation (9) are excellent; with coefficients of determination of ≈ 1.0 (the reader can find details of these results in Mazzeo & Venegas, 1991). Coefficients A_j (j=0,…6) depend on surface roughness and atmospheric stability. Plotting the values of A_j vs (z_0/L) (z_0 is the surface roughness length and L is the Monin-Obukhov´s length) the expressions of A_j (z_0/L) included in Table 1 have been obtained

The following expressions are considered for the wind speed and the eddy diffusivity (Arya, 1999):

$$u(z) = \frac{u_*}{k_v}\left[\ln\left(\frac{z}{z_0}\right) + \Psi\left(\frac{z}{L}\right)\right] \tag{10}$$

$$K(z) = \frac{k_v \; u_* \,(z+z_0)}{\varphi\left(\frac{z}{L}\right)} \tag{11}$$

where u_* is the friction velocity, k_v is the von Karman´s constant (=0.41), $\Psi(z/L)$ functions determine stability correction due to stratification and $\varphi(z/L)$ is the dimensionless wind shear (Wieringa, 1980; Gryning et al., 1987):

$$\Psi\left(\frac{z}{L}\right)=\begin{cases} 6.9\dfrac{z}{L} & \dfrac{z}{L}>0 \\ 1-\varphi^{-1}\left(\dfrac{z}{L}\right) & \dfrac{z}{L}<0 \end{cases}$$

$$\varphi\left(\frac{z}{L}\right)=\begin{cases} 1+6.9\dfrac{z}{L} & \dfrac{z}{L}>0 \\ \left(1-22\dfrac{z}{L}\right)^{-\frac{1}{4}} & \dfrac{z}{L}<0 \end{cases}$$

$\Psi(0)= 0$ and $\varphi(0)= 1$.

Substituting Equations (8) and (11) into Equation (6) and operating, the following expression for C(x,0) can be obtained:

$$C(x,0)=\frac{Q\ h(x)}{|A_1|\,k_v\ u_*\,z_0} \tag{12}$$

C(x,0) can be estimated from Equation (12) knowing the form of h(x). Therefore, considering the equation of pollutant mass continuity expressed by (Pasquill & Smith, 1983):

$$\int_0^x Q\,dx=\int_{z_o}^h u(z)\,C(x,z)\,dz \tag{13}$$

and Equations (8), (10) and (12) along with the boundary condition C(x,h)=0, the following expression can be obtained when Q= constant:

$$\frac{x}{z_0}=\frac{1}{|A_1|\,k_v^2}\left(\frac{h}{z_0}\right)^2 G\left(\frac{z_0}{h};\frac{h}{L}\right) \tag{14}$$

The form of $G(z_0/h;\ h/L)$ is not simple (the complete expression is included in Mazzeo & Venegas, 1991), however the values of (h/z_0) computed from Equation (14) can be fitted with great accuracy (coefficient of determination ≈1) to potential functions (Mazzeo & Venegas, 1991) given by:

$$\frac{h}{z_0}=a\left(\frac{x}{z_0}\right)^b \tag{15}$$

a and *b* depend on atmospheric stability. The expressions for $a(z_0/L)$ and $b(z_0/L)$ are included in Table 2.

Atmospheric stability	Expressions for $a(z_0/L)$ and $b(z_0/L)$
$z_0/L < -10^{-4}$	$a = 3.618833 + 0.2369076 \ln(\lvert z_0/L \rvert)$ $b = 0.5356147 + 0.0234187 \ln[(\lvert z_0/L \rvert) + 0.01]$
$-10^{-4} \le z_0/L \le 10^{-4}$	$a = -384.73\,(z_0/L) + 1.4$ $b = -130.0\,(z_0/L) + 0.415$
$10^{-4} < z_0/L$	$a = 0.6224632 + 7.37387\times10^{-5} / \ln[(z_0/L) + 1]$ $b = 0.5065736 - 1.196137 / \ln[2802.315 + 9/(z_0/L)]$

Table 2. Expressions of $a(z_0/L)$ and $b(z_0/L)$ as functions of (z_0/L).

Substituting Equation (15) in Equation (12), it becomes:

$$C(x,0) = \frac{a\ Q\ (x/z_0)^b}{\lvert A_1 \rvert\ k_v\ u_*} \tag{16}$$

which is the expression for a semi-infinite area source emitting continuously with a uniform strength (Q). The expression for a finite and continuous source located between x= 0 and x= x_1, with strength Q, can be derived from Equation (16) by subtracting the concentration due to a continuous semi-infinite source with strength Q lying through $x>x_1$, from Equation (16):

$$C(x,0) = \frac{a\ Q\left[x^b - (x - x_1)^b\right]}{\lvert A_1 \rvert\ k_v z_0^b u_*} \tag{17}$$

In an urban area, we may assume horizontal distribution of area sources with strength varying according to a typical square grid pattern. Each grid square has a uniform strength Q_i (i = 0, 1, 2, …, N). The variation of the concentration with x, for $x > x_i$ (i = 0, 1, 2, …, N) is given by:

$$C(x,0) = \frac{a\left[Q_o x^b + \sum_{i=1}^{N} (Q_i - Q_{i-1})(x - x_i)^b\right]}{\left(\lvert A_1 \rvert k_v z_o^b u_*\right)} \tag{18}$$

The form of C(x,z) can be obtained substituting Equation (18) into Equation (8),

$$C(x, z) = \frac{a\left[Q_o x^b + \sum_{i=1}^{N} (Q_i - Q_{i-1})(x - x_i)^b\right]}{\left(\lvert A_1 \rvert k_v z_o^b u_*\right)} \sum_{j=0}^{6} A_j \left(\frac{z}{h}\right)^j \tag{19}$$

A constant wind direction is required for application of Equations (18) and (19). It has been noted from applications of Equation (18) that estimated concentration at any receptor is mainly originated from the emission in the grid square in which the receptor is located. This is because area source distributions in a city are generally fairly smooth and, the contribution of upstream grid squares (from Equation (18)) rapidly reduces with distance to the receptor. The simplification of assuming that the uniform area source strength Q_i only varies with x (in the wind direction), suppose to consider the "narrow plume" hypothesis.

This assumption has also been included in other simple urban dispersion models (Gifford, 1970, Gifford & Hanna, 1973, Arya, 1999).
The performance of DAUMOD model in estimating background concentrations has been evaluated comparing estimated and observed concentration data from several cities. Results for Bremen (Germany), Frankfurt (Germany) and Nashville (USA) have been reported in Mazzeo & Venegas (1991) and for Copenhagen (Denmark) can be found in Venegas & Mazzeo (2002). The validation of the application of DAUMOD to estimate NO_x, CO and PM_{10} in Buenos Aires City can be found in Mazzeo & Venegas (2004), Venegas & Mazzeo (2006) and Venegas & Martin (2004). Results show that the performance of the model in estimating short-term concentrations (hourly and daily) is good and it improves when estimating long averaging time values (monthly and annual).
At present, photochemical transformations involving NO, NO_2 and O_3 are not included in DAUMOD model. However, output concentrations of NO_2 are calculated on the basis of an empirical relationship between NO_2 and NO_x (Derwent & Middleton, 1996; Dixon et al., 2001; Middleton at al., 2008). The concentration of NO_2 is calculated using the polynomial expression (Derwent & Middleton, 1996, CERC, 2003):

$$[NO_2] = 2.166 - [NO_x]\,(1.236 - 3.348\,B + 1.933\,B^2 - 0.326\,B^3)$$

where $B = \log_{10}([NO_x])$ and $[NO_x]$ is hourly-averaged concentration in ppb.

The AERMOD model
AERMOD (EPA, 2004) is a steady-state plume dispersion model for assessment of pollutant concentrations from a variety of sources. AERMOD simulates transport and dispersion from multiple point, area or volume sources based on an up-to-date characterization of planetary boundary layer (PBL). AERMOD's concentration formulations consider the effects from vertical variations in wind, temperature and turbulence. These profiles are represented by "effective" values constructed by averaging over the layer through which plume material travels directly from the source to receptor. Sources may be located in rural or urban areas, and receptors may be located in simple or complex terrain. The model employs hourly sequential pre-processed meteorological data to estimate concentrations for averaging times from one hour to one year (also multiple years). AERMOD is designed to operate in concert with two pre-processor codes: AERMET processes meteorological data for input to AERMOD, and AERMAP processes terrain elevation data and generates receptor information for input to AERMOD. AERMOD is applicable to primary pollutants and continuous releases of toxic and hazardous waste pollutants. Chemical transformation is treated by simple exponential decay. A more complete description of AERMOD model can be found in EPA (2004) and Cimorelli et al. (2005).
In stable boundary layer (SBL), the concentration distribution is assumed to be Gaussian, both vertically and horizontally. During stable conditions (i.e., stable and neutral stratifications, when $L > 0$), AERMOD estimates concentrations (C_s) from:

$$C_s(x,y,z) = \frac{Q_p}{\sqrt{2\pi}\,\tilde{u}\,\sigma_{zs}} F_y \times \sum_{m=-\infty}^{\infty} \left\{ \exp\left[-\frac{(z - h_{es} - 2mz_{ieff})^2}{2\sigma_{zs}^2} \right] + \exp\left[-\frac{(z + h_{es} + 2mz_{ieff})^2}{2\sigma_{zs}^2} \right] \right\} \tag{20}$$

where, Q_P is the point source emission rate, ũ is the effective wind speed, z_{ieff} is the effective mechanical mixing height, σ_{zs} is the total vertical dispersion, h_{es} is the plume height (Weil, 1988; Cimorelli et al, 2005) and F_y is the lateral distribution functions.
In the convective boundary layer (CBL), the horizontal distribution is assumed to be Gaussian, but vertical distribution is described with a bi-Gaussian probability density function (Willis & Deardoff, 1981; Briggs, 1993). In CBL the transport and dispersion of a plume is characterized as the superposition of three modelled plumes: the direct plume (from the stack), the indirect plume, and the penetrated plume, where the indirect plume accounts for lofting of a buoyant plume near the top of boundary layer, and the penetrated plume accounts for the portion of a plume that, due to its buoyancy, penetrates above the mixed layer, but can disperse downward and re-enter the mixed layer. In the CBL, plume rise is superposed on the displacements by random convective velocities (Weil et al, 1997).
The total concentration (C_c) in the CBL is found by adding the contribution from three sources: a "direct" source, an "indirect" source and a "penetrated" source (above the CBL top). For the horizontal plume state,

$$C_c(x,y,z)=C_d(x,y,z)+C_r(x,y,z)+C_p(x,y,z) \tag{21}$$

The concentration (C_d) due to the direct plume is given by

$$\begin{aligned} C_d(x,y,z) &= \frac{Q_P\, f_p}{\sqrt{2\pi}\tilde{u}\sigma_y} \exp\left[-\frac{y^2}{2\sigma_y^2}\right] \\ &\text{x} \sum_{j=1}^{2}\sum_{m=0}^{\infty}\frac{\lambda_j}{\sigma_{zj}}\left\{\exp\left[-\frac{\left(z-\Psi_{dj}-2mz_i\right)^2}{2\sigma_{zj}^2}\right]+\exp\left[-\frac{\left(z+\Psi_{dj}+2mz_i\right)^2}{2\sigma_{zj}^2}\right]\right\} \end{aligned} \tag{22}$$

where $\Psi_{dj}= h_s + \Delta h_d + \overline{w_j}\, x/\tilde{u}$ is the height of the direct source plume, ũ is the effective wind speed, Z_i is the mixing height, Δh_d is the plume rise and $\overline{w_j}$ is the vertical velocity. The subscript j is equal to 1 for updrafts and 2 for downdrafts with λ_j defined as the weighting coefficient for each distribution:

$$\lambda_1 = \frac{\overline{w_2}}{\overline{w_2}-\overline{w_1}} \tag{23}$$

$$\lambda_2 = -\frac{\overline{w_1}}{\overline{w_2}-\overline{w_1}} \tag{24}$$

Equation (22) uses an image plume to handle ground reflections by assuming a source at $z = -h_s$. All subsequent reflections are handled by sources at $z=2z_i+h_s$, $-2z_i - h_s$, $4z_i + h_s$, $-4z_i-h_s$ and so on. The factor f_p accounts for the fraction of source material that does not penetrate the top of the CBL.

The concentration (C_r) due to the indirect source is calculated from

$$C_r(x,y,z)=\frac{Q_P\, f_p}{\sqrt{2\pi}\tilde{u}\sigma_y}\exp\left[-\frac{y^2}{2\sigma_y^2}\right] \times \sum_{j=1}^{2}\sum_{m=0}^{\infty}\frac{\lambda_j}{\sigma_{zj}}\left\{\exp\left[-\frac{(z+\Psi_{rj}-2mz_i)^2}{2\sigma_{zj}^2}\right]+\exp\left[-\frac{(z-\Psi_{rj}+2mz_i)^2}{2\sigma_{zj}^2}\right]\right\} \tag{25}$$

where σ_{zj} and F_y are the same as defined for the direct source, the plume height $\Psi_{rj}= h_s + \Delta h_r + \overline{w}_j\, x/\tilde{u}$ (j=1 ,2) with $\Delta h_r= \Delta h_d - \Delta h_i$ and Δh_i is the indirect source plume rise.

For the penetrated source, the vertical and lateral concentration distributions have a Gaussian form, such that the concentration (C_p) is given by

$$C_p(x,y,z)=\frac{Q_P(1-f_p)}{\sqrt{2\pi}\tilde{u}\sigma_{yp}\sigma_{zp}}\exp\left[-\frac{y^2}{2\sigma_{yp}^2}\right] \times \sum_{m=-\infty}^{\infty}\left\{\exp\left[-\frac{(z-h_{ep}-2mz_{ieff})^2}{2\sigma_{zp}^2}\right]+\exp\left[-\frac{(z+h_{ep}+2mz_{ieff})^2}{2\sigma_{zp}^2}\right]\right\} \tag{26}$$

where h_{ep} is the height of the penetrated plume height and z_{ieff} is the height of the upper reflecting surface in a stable layer.

For flow in complex terrain, AERMOD incorporates the concept of a dividing streamline (Snyder et al., 1985), and the plume is modelled as a combination of terrain-following and terrain-impacting states. This approach has been designed to be physically realistic and simple to implement while avoiding the need to distinguish among simple, intermediate and complex terrain. As result, AERMOD removes the need for defining complex regimes; all terrain is handled in a consistent and continuous manner that is simple while still considering the dividing streamline concept in stably-stratified conditions.

The model considers the influence of building wakes and it enhances vertical turbulence to account for the "convective like" boundary layer found in night-time urban areas.

4.4. Annual concentration distributions in the city of Buenos Aires

Hourly urban background concentrations of NO_2, CO and PM_{10} at each grid square (1 x 1 km) in which the city of Buenos Aires has been divided, are estimated applying the two atmospheric dispersion models described above. DAUMOD model is applied to compute area source emissions contribution and AERMOD to estimate point sources contribution. Hourly data registered at the meteorological station of the domestic airport (located in the city) and the emissions inventory for Buenos Aires city (Section 4.2.) have been used in calculations. Figs. 5, 6 and 7 show the horizontal distributions of computed mean annual NO_2, CO and PM_{10} concentrations within the city of Buenos Aires. High concentration values can be found downtown and near the main train stations in the city, where there are usually more activity and traffic. The NO_2, CO and PM_{10} concentration patterns show large spatial variability that is mainly related to the distribution of area sources emissions. Higher concentration values are related to higher traffic density area.

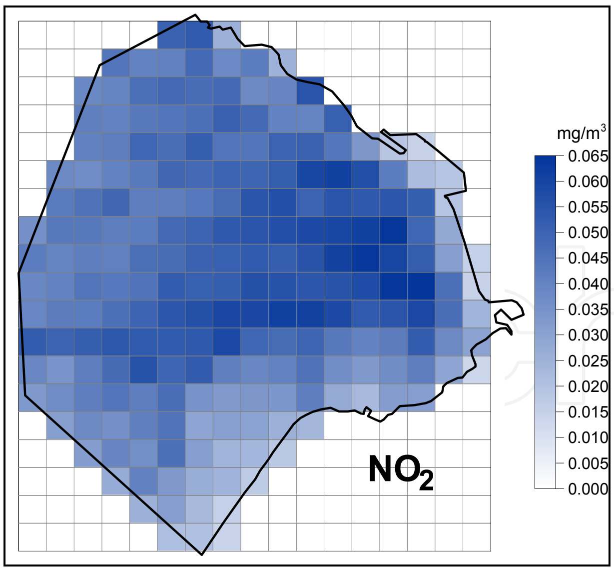

Fig. 5. Mean annual background concentrations of NO_2 in Buenos Aires city.

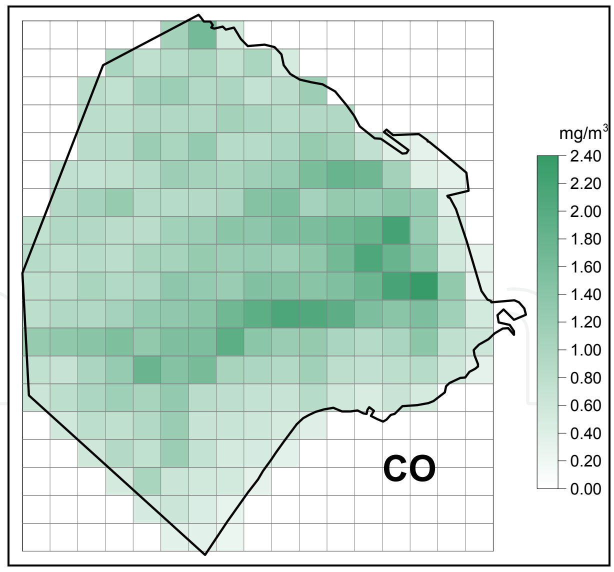

Fig. 6. Mean annual background concentrations of CO in Buenos Aires city.

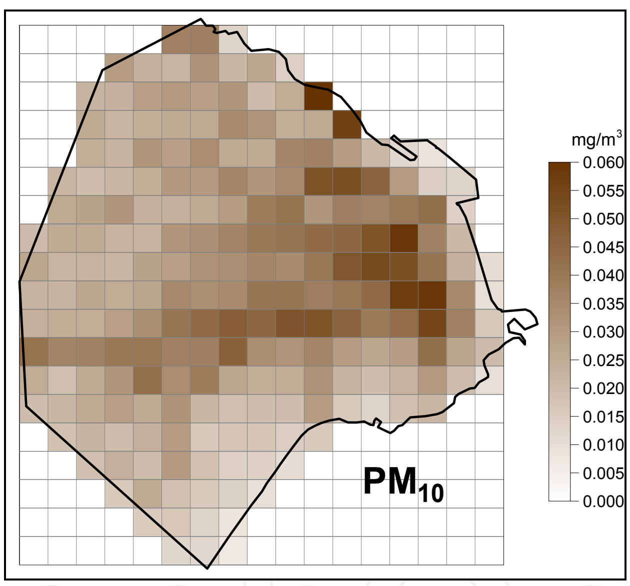

Fig. 7. Mean annual background concentrations of PM_{10} in Buenos Aires city.

4.5. Application of the methodology for designing the air quality monitoring network

The site selection proposed methodology described in Section 3 has been applied to determine the site locations for monitoring 1-h average NO_2 concentration (k=1), 1-h (k=2) and 8-h (k=3) average CO concentrations and 24-h average PM_{10} concentration (k=4) in the atmosphere of the city of Buenos Aires, greater than reference concentration levels.

Reference concentration levels have been selected considering the Air Quality Guidelines established by the World Health Organization (W.H.O., 2000, 2006). A weighing factor (ω_j) of 1 is assigned to the Air Quality Guideline levels. Table 3 presents the reference concentration levels and the corresponding weighing factors for the three pollutants considered. According to the proposed methodology, in this application, M=4 and n_k=7.

Weighing factor (ω_j)	NO_2 (averaging time: 1h)	CO (averaging time: 1h)	CO (averaging time: 8h)	PM_{10} (averaging time: 24h)
	mg/m^3	mg/m^3	mg/m^3	mg/m^3
0.5	0.10	15	5	0.025
0.7	0.14	21	7	0.035
0.9	0.18	27	9	0.045
1.0	0.20	30	10	0.050
1.2	0.24	36	12	0.060
1.5	0.30	45	15	0.075
2.0	0.40	60	20	0.100

Table 3. Reference concentration levels and weighing factors (ω_j) for NO_2 (averaging time: 1h), CO (averaging times: 1h and 8h) and PM_{10} (averaging time: 24h).

The values of 1-h average NO_2 concentrations, 1-h and 8-h average CO concentrations and 24-h average PM_{10} concentrations ($C_{i,k}$) are estimated for each grid square in which the city has been divided applying DAUMOD and AERMOD atmospheric dispersion models.
Using model estimations of ($C_{i,k}$) and data on Table 3, the values of the exceedance score ES_k (Equation (1)) for each combination (air pollutant, averaging time) (k=1,...,4) are estimated for each grid square. Fig. 8 presents the horizontal distribution of the total exceedance score ($ES= ES_1 + ES_2 + ES_3 + ES_4$) in the urban area.
In order to evaluate the population factor (PF) given by Equation (3), the horizontal distribution of population density ($inhab/km^2$) in the city has been elaborated using the information of the last National Census (INDEC, 2008). Fig. 9 shows the horizontal distribution of the population factor (PF) in the city of Buenos Aires.

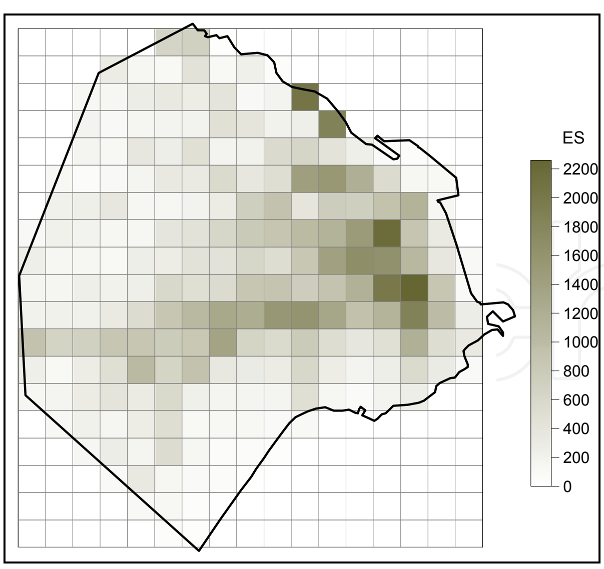

Fig. 8. Horizontal distribution of the total exceedance score ($ES = \sum_{k=1}^{4} ES_k$) in the city of Buenos Aires.

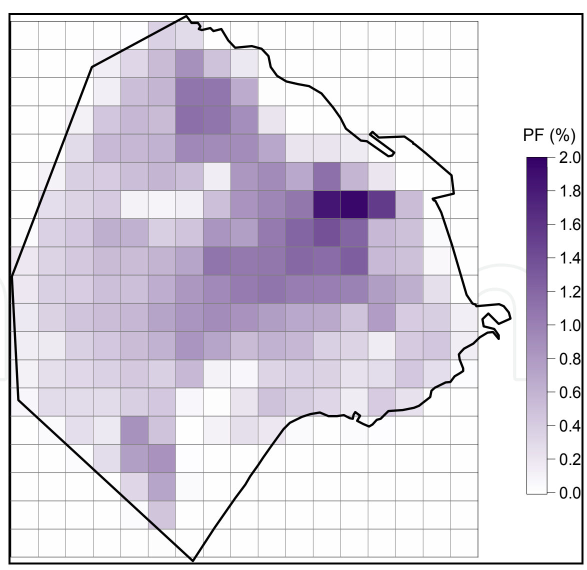

Fig. 9. Horizontal distribution of the population factor (PF) in the city of Buenos Aires.

In this way, knowing the total exceedance score (ES) and the population factor (PF) for each grid square, the horizontal distribution of the total score (TS= PFxES) (Fig. 10) is estimated using Equation (4). A preliminary monitoring network configuration is defined considering a budget constraint that limits the number of monitoring sites to twelve. The location of the 12 stations is obtained maximizing TS and considering a minimum distance of D=1km between two sensors of the same pollutant. Fig. 11 shows the monitoring sites of the preliminary network.

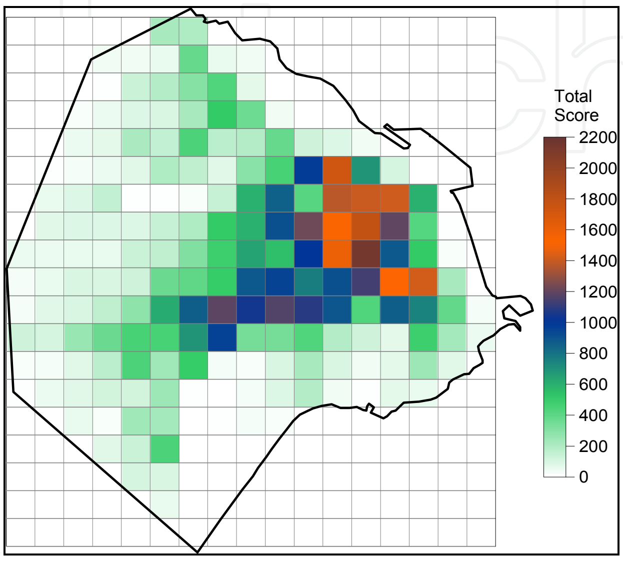

Fig. 10. Horizontal distribution of the Total Score (TS) in the urban area.

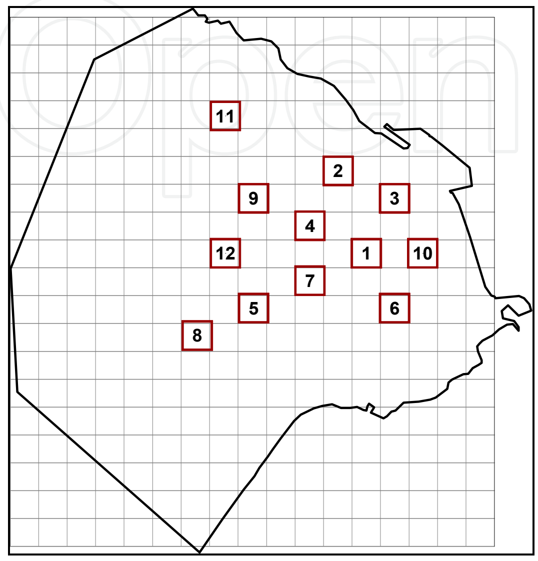

Fig. 11. Monitoring locations selected considering the total score and the distance constraint (preliminary configuration).

The final configuration of the proposed monitoring network is defined comparing the mean concentration of each pollutant at near preliminary sites, using the t-test. If the difference between average concentrations at two nearby sites is statistically significant at the 99% confidence level, both sites remain in the final network configuration. Otherwise, the site with lower TS can be discarded. Tables 4 and 5 show if the difference between average concentrations at a pair of near sites is statistically significant at the 99% (Yes:Y, No: N).

NO_2	1	2	3	4	5	6	7	8	9	10	11	12
1		Y	Y	Y		Y	Y			Y		
2			Y	Y					Y		Y	
3				Y		N				Y		
4					N		Y		Y		Y	Y
5						Y	Y	Y	Y			Y
6							N			Y		
7									N			Y
8												Y
9											Y	Y
10												
11												N

CO	1	2	3	4	5	6	7	8	9	10	11	12
1		Y	Y	Y		Y	Y			Y		
2			Y	Y					Y		Y	
3				Y		N				N		
4					Y		Y		Y		Y	Y
5						Y	Y	Y	Y			Y
6							N			N		
7									N			Y
8												Y
9											Y	Y
10												
11												Y

Table 4. It is indicated if the difference between the average concentrations at two nearby monitoring locations is statistically significant at the 99% confidence level (Y: yes; N: no)

PM_{10}	1	2	3	4	5	6	7	8	9	10	11	12
1		N	Y	Y		Y	Y			Y		
2			Y	Y					Y		Y	
3				N		Y				Y		
4					N		Y		Y		Y	Y
5						N	Y	Y	Y			Y
6							Y			N		
7									N			Y
8												Y
9											Y	Y
10												
11												N

Table 5. It is indicated if the difference between the average concentrations at two nearby monitoring locations is statistically significant at the 99% confidence level (Y: yes; N: no)

Fig. 12 shows the proposed monitoring sites and the pollutants to be measured at each site according to results on Tables 4 and 5.

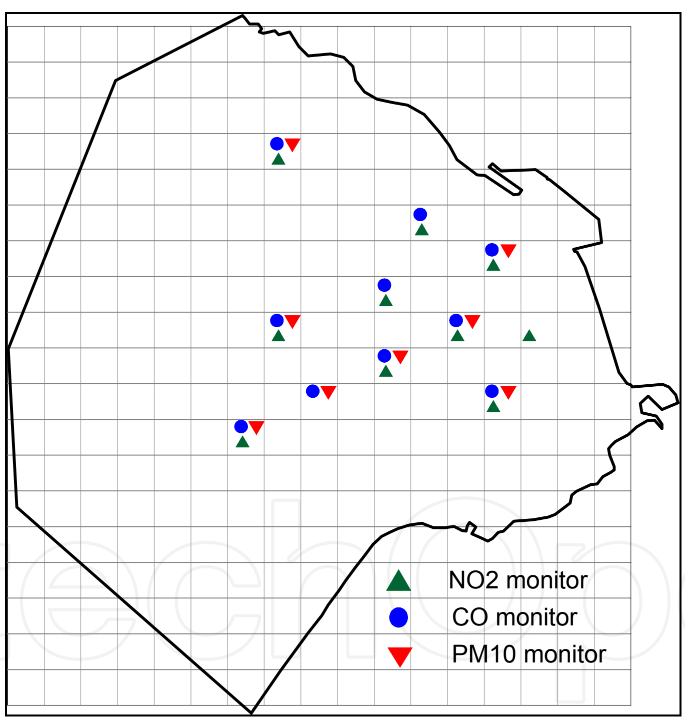

Fig. 12. Sites chosen to locate an air quality monitoring station and pollutants to be measured.

Once the proposed network (Fig. 12) is in operation, the environmental authority of the city may be interested to know the horizontal extension of the "spatial representativeness" of mean concentration values registered at each monitoring site. Figs. 13, 14 and 15 shows the areas near each monitoring site where the NO_2, CO and PM_{10} mean concentrations cannot be considered statistically significant different at the 99% confidence level, obtained after the application of the t-Student test.

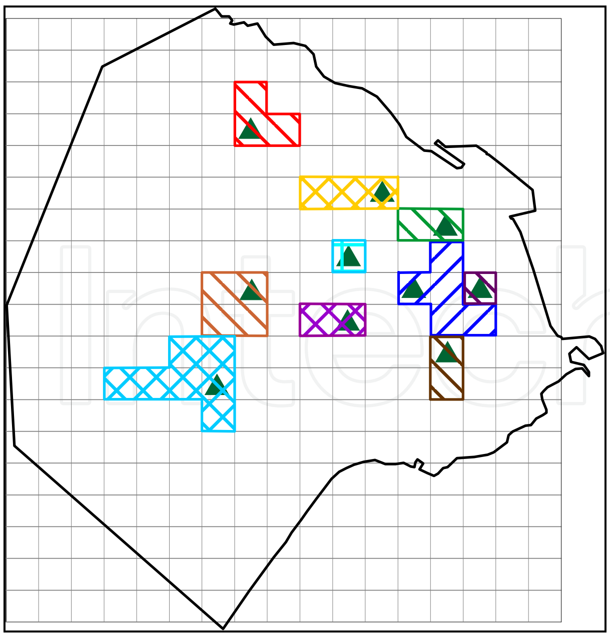

Fig. 13. “Spatial representativeness” for NO_2 monitoring stations (▲).

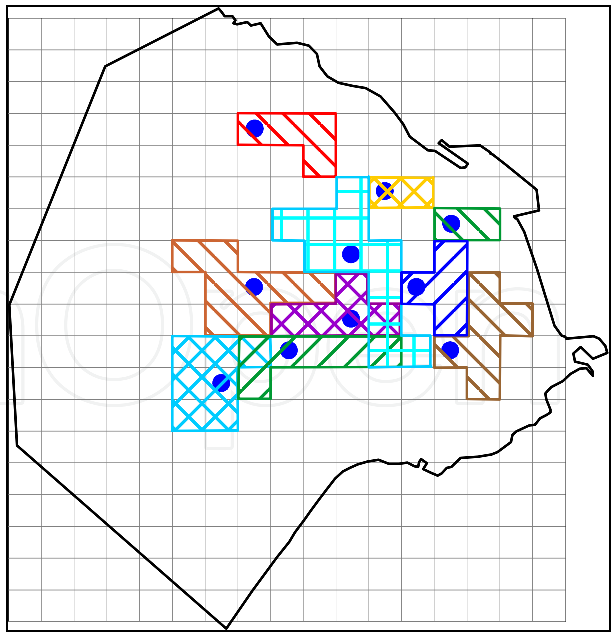

Fig. 14. “Spatial representativeness” for CO monitoring stations (●).

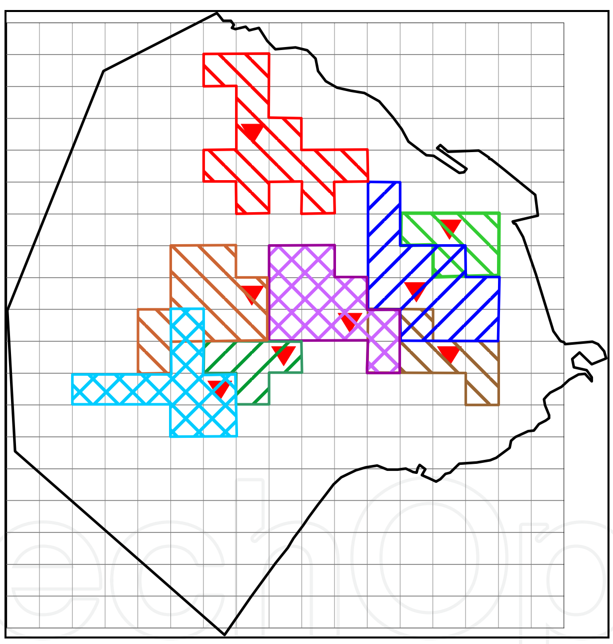

Fig. 15. “Spatial representativeness” for PM_{10} monitoring stations (▼).

5. Conclusion

A multiple objective and multi-pollutant planning procedure for designing an urban air quality monitoring network is presented in this study. The considered monitoring objectives are to maximize the “detection capability” of higher pollutant concentrations and the “protection capability” for areas with higher population density. The design methodology is based on the analysis of air pollutant concentrations estimated by atmospheric dispersion models. It simultaneously considers an exceedance score and a population factor. A statistical analysis is used for optimization.

The methodology is applied to design a NO_2, CO and PM_{10}, monitoring network for the city of Buenos Aires considering a spatial resolution (for the emission inventory and model estimations) of 1 x 1km. Air pollutant concentrations in the city have been estimated using the DAUMOD and AERMOD atmospheric dispersion models, that evaluate the contribution of area and point sources, respectively.

The optimal alternative of the proposed network can be summarized as: a) seven locations for monitoring NO_2, CO and PM_{10}; b) two sites for NO_2 and CO; c) one location for CO and PM_{10} and d) one station for NO_2 only. The "spatial representativeness" of mean concentrations at monitoring sites varies with each pollutant: a) for NO_2, between 1-7km^2; b) for CO between 2-11km^2 and c) for PM_{10}, between 4-12km^2.

It must be noted that the ultimate decision in site selection is left to the air quality monitoring authority.

Future studies could be focused on: a) the evaluation of how sensitive is the proposed methodology for air quality network design to slight changes in the input data (e.g. the weighing factors, the spatial resolution) and b) the inclusion of other optimization objectives (e.g. land use, frequency of violations of air quality standards, protect damage to vulnerable receptors as historic and/or artistic valuable property).

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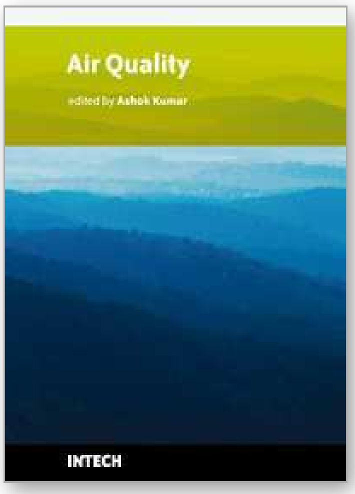

Air Quality
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Air pollution is about five decades or so old field and continues to be a global concern. Therefore, the governments around the world are involved in managing air quality in their countries for the welfare of their citizens. The management of air pollution involves understanding air pollution sources, monitoring of contaminants, modeling air quality, performing laboratory experiments, the use of satellite images for quantifying air quality levels, indoor air pollution, and elimination of contaminants through control. Research activities are being performed on every aspect of air pollution throughout the world, in order to respond to public concerns. The book is grouped in five different sections. Some topics are more detailed than others. The readers should be aware that multi-authored books have difficulty maintaining consistency. A reader will find, however, that each chapter is intellectually stimulating. Our goal was to provide current information and present a reasonable analysis of air quality data compiled by knowledgeable professionals in the field of air pollution.

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